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Incremental Dynamic Analysis of Low and Medium Rise Reinforced Concrete Buildings

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Abstract: The probabilistic seismic risk analysis is an estimation of the damage probability and losses occurred due to the earthquake event. The evaluation of the buildings in the probabilistic terms is essential in the high seismic regions to check the performance due to the uncertainties of occurrence, type and intensity. In more recent times to ascertain more methodologically the performance of Structures, Incremental dynamic Analysis has emerged as a better choice. In the present paper a low and medium rise building is considered and analyzed by carrying out nonlinear time history analysis by scaling the PGA from 0.2g to 1.4g at an interval of 0.2g for the selected set of earthquake records. The response of low and medium rise buildings with different support conditions for different damage measures are compared for maximum roof floor acceleration, Maximum Inter story drift ratio and maximum Isolator displacement.

Keywords: *Seismic risk, IDA, low and medium rise, PGA, floor acceleration.*

1. Introduction:

The natural hazard, Earthquakes, which are unpredictable, extremely destructive compared with other natural disaster types, and the activity of which threaten the sustainable development of humans. The damage caused to the modern engineered structures by the past destructive earthquakes has shown the vulnerability of the buildings to this natural phenomenon. Buildings are the major structures that are exposed to damage when earthquakes are triggered. Earthquakes can never be avoided or predicted in advance, but damages caused can be prevented to a large extent, if preventive measures are taken. The performance anticipated under seismic forces is presented in figure. The Structures which are exposed to minor earthquakes shall be designed to withstand minor earthquakes with minimal damage. Structures are designed to withstand moderate earthquakes with some damage, but still remain functional. Under severe earthquakes Structures are designed to withstand significant damage, but prevent collapse.

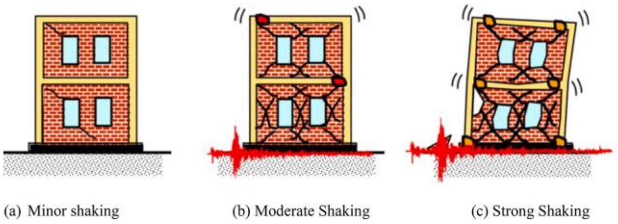

Fig 1. (a), (b), and (c) displaying the performance objectives

2. Incremental Dynamic Analisis

Incremental Dynamic Analysis referred as IDA, is the parametric analysis technique which have lately developed in different forms for evaluating more methodically the structural performance under earthquake loads. In IDA, a structural model is subjected few or more ground motion records, each scaled to several levels of intensity, thus creating one or more curves of response versus intensity level [1]. Incremental Dynamic Analysis a powerful tool for assessing the variation in seismic demand and capacity of non-deterministic structural models, building upon existing procedures with Monte Carlo simulation with approximate moment-estimation [2]. Performing Incremental Dynamic Analysis for a structural model includes carrying out nonlinear dynamic analyses of the structural model with a set of ground motion records, increased gradually to increase intensity levels, selected to force the structure to display the complete range of behavior, from elasticity to the possible global dynamic instability [3].

Vamvatsikos and Cornell introduced IDA [1] however, the concept of earthquake load scaling had been earlier used by many authors such as Bertero [4]. The concept used by them to assess mostly is the behavior of structural frames in the buildings. With numerous advantages, IDA has posed challenges that need to be overcome. To have an accurate IDA curve, numerous amounts of nonlinear time history analyses (NTHA) are necessary, to provide adequate accuracy in the seismic demand estimation, for this purposes several records shall be utilised [5].

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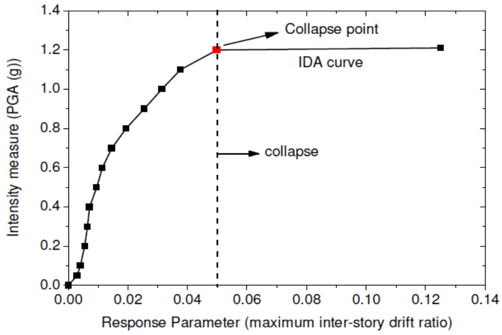

Fig 2. IDA Curve for single earthquake record.

IDA is a computer analysis technique which is widely used in the comprehensive evaluation of the seismic performance of structures under the seismic loads. This concept was primarily bought up by Bertero [4] and later comprehend and applied by Vamvatsikos and Cornell [1] for performance-based earthquake engineering. IDA allows for the determination of the structure's capacity curves and its performance at various seismic intensity levels, offering critical insights into the potential structural vulnerabilities In the IDA, numbers of NTHAs are performed under a suite of earthquake records, which are scaled by a constant scale factor to incrementally enhance the intensity of seismic data. The intensity is increased up to a specified level of interest or until the structure reaches to the global collapse state. Several intensity measures are prescribed to quantify the intensity values of the ground motion, such as PGA, PGV, PGD, etc. Thus, in this way a curve between the ground motion is plotted against the structural response parameter or damage measure (e.g., inter-storey drift or roof drift ratio), which is known as IDA curve as shown in figure 2[6].

Incremental Dynamic Analysis contains exposing the structural model to ground motions each scaled up to desired multiple levels. The resulting a curve that displays the Engineering Demand Parameter (EDP) graphed against the Intensity Measure (IM) which is used to control the incremental values of the ground motion (PGA). Incremental Dynamic Analysis can be carried out for a adequate number of seismic ground motions to achieve statistical evaluation of the results. By effectively summarizing the IDA curves, establishing limit-states, and integrating the outcomes with Probabilistic Seismic Hazard Analysis, the expected objectives can be achieved [5].

3. MODEL DESCRIPTION AND ANALYSIS

For the present study, a low rise building (5 floors) and medium rise building (13 floors) concrete building with base fixed and isolated (with Lead rubber bearing) are considered. Time history analysis is carried out by employing fast nonlinear analysis (FNA) using the commercial structural analysis package ETABS [7]. The columns, as well as the beams, are modeled as line elements, while the lift core walls are modeled as shell elements. The floor slab is considered to be a rigid diaphragm and is modeled as a membrane element for the column beam slab system [7]. The typical plan view and sectional views of low rise and medium rise buildings with base fixed and isolated with lead rubber bearings are shown in figure 4 to 8. The material properties used for modeling the building, along with other details of the, are specified in table 1. The Isolator properties designed for low and medium rise building considering the reactive forces are given in table 2. Figure 9 shows the typical section view of a Lead rubber bearing [8,9]. A set of seven, time histories or earthquake records is selected for the current study (refer table 4). These ground motion records of major earthquakes were taken from the strong motion database of the Berkeley Pacific Earthquake Engineering Research Centre (PEER) (*Pacific earthquake engineering research center (PEER) strong motion database*) and the Centre for Engineering Strong Motion [10]. An artificial accelerogram is generated using an application - SeismoArtif [11]to match response spectrumof 1893-2016[12]. Figure 3 displays the typical time history plot for a recorded earthquake data.

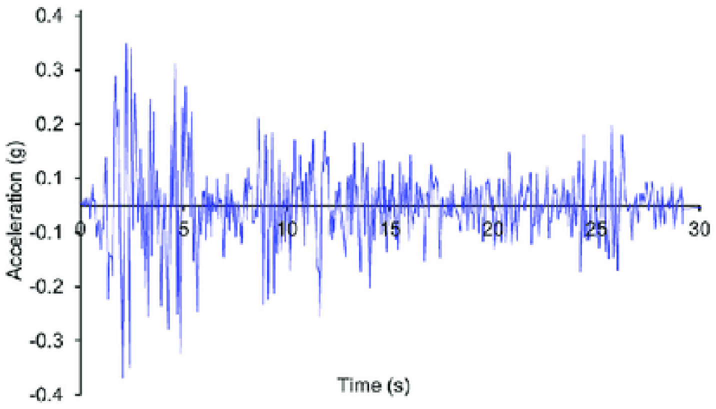

Fig 3. Typical time history plot of a recorded earthquake

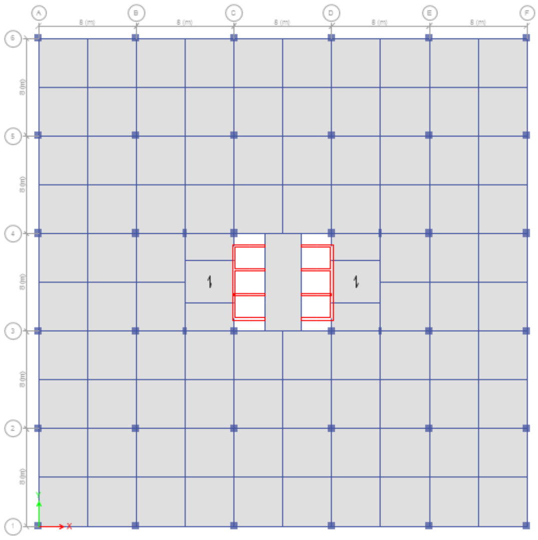

Fig 4. Plan View of the Five and Thirteen floor building

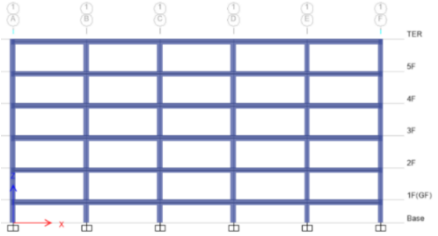

Fig 5. Sectional view of low rise building with fixed base

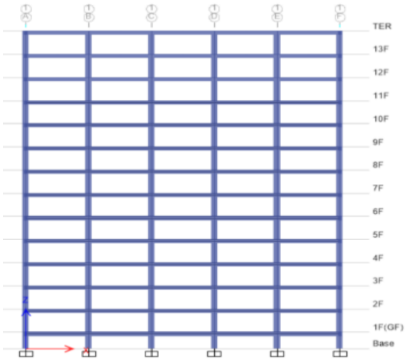

Fig 6. Sectional view of medium rise building with fixed base

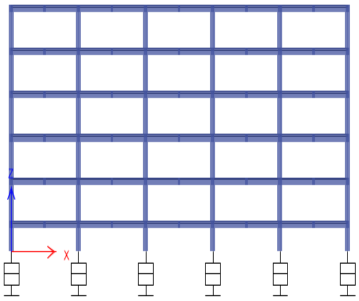

Fig 7. Sectional view of low rise building with isolated base

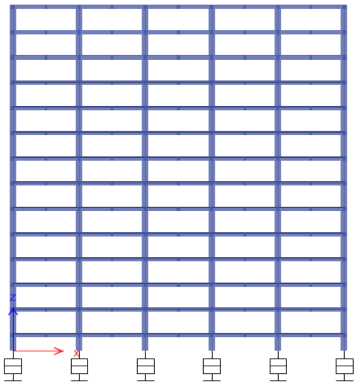

Fig 8. Sectional view of medium rise building with isolated base

Table 1: Building properties considered for Analysis[16]

Building Type	Reinforced concrete framed building	
Number of floors	5 Floors (**low rise**)	13 Floors (**medium rise)**
Total height of building from foundation level	20 m	48 m
Height of each floor	3.5 m	
Bay width	8.0 m	

Number of Bays	5	
Depth of Foundation	2.5 below GL	
Column size	600x600 mm	800x800 mm
Main Beam Size	450x600 mm	
Secondary Beam Size	300x600 mm	
Flat slab thickness	300 mm	
Material Properties[13]		
Grade of concrete	M40	
Grade of reinforcing steel	Fe 500	
Loads		
Dead Load[14]	Self-weight+ floor finishes + walls load	
Live Load[15]	5.0 kN/sqm (commercial building)	

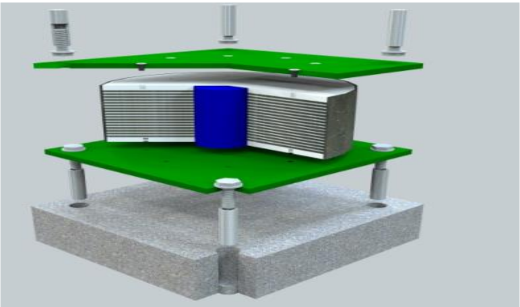

Fig 9. Image showing LRB Isolators (https://doshinrubber.com/)

Table 2: Isolator properties for Five and Thirteen floor building

Sl No	Description			Low rise building	Medium rise building
	Direction: U1				
1	Vertical stiffness,	K_V	=	7460448.067 kN/m	10743045.216 kN/m
2	Effective damping	ξ_{eff}	=	15.00 %	15.00 %
	Direction: U2 & U3				
	Linear Property				
3	Effective horizontal stiffness,	K_{eff}	=	2828.282 kN/m	5513.696 kN/m
4	Effective damping of bearing,	ξ_{eff}	=	15.00 %	15.00 %
	Non-Linear Property				
5	Initial stiffness,	K_e	=	40349.831 kN/m	58103.756 kN/m
6	Yield force,	F_y	=	235.275kN	518.335 kN
7	Post yield stiffness ratio		=	0.1	0.1

Table 3. Time history data of the selected earthquakes for carrying out the time history analysis[16]

Earthquake	Max. Acceleration (g)	Max. Velocity (cm/sec)	Max. Displacement (cm)
Bhuj (2001)	0.10	11.19	18.15
Chamoli (1999)	0.19	11.20	5.18

Chichi (1999)	0.36	21.54	21.88
Elcentro (1979)	0.32	62.99	56.50
Kobe (1995)	0.33	27.67	9.54
Loma Prieta (1989)	0.35	44.28	19.04
Northridge (1994)	0.57	51.82	9.00
IS- 1893 (matched)	0.20	15.42	34.18

4. Damage Measure, Damage States and Intensity Measure

To assess degree of damage occurred due to the earthquake input, it is important to define the damage measures (DM) or the engineering demand parameters (EDP) which can depict the building response in the elastic and inelastic states. To estimate damage of the base-isolated low and medium rise building reasonably, five damage measures are considered including: (i) maximum inter-storey drift ratio (MID), which shows superstructure damage with architectural distortion; (ii) maximum roof drift ratio (MRDR), which indicates the possibility of pounding effect;(iii) maximum isolator displacement (MID), which depicts the safety of the isolation system; (iv) maximum top floor acceleration (MRFA), which provides the degree of discomfort felt by occupants of building and, damage caused to interior contents and machinery; and (v) maximum base shear (MBS), an important EDPs especially for base isolated buildings for economic design of foundations.

With the purpose to describe damage condition in the base-isolated building frame, four damage states (DS) are considered namely, non-structural, slight, moderate, and extensive [17] for each damage measure. The deterministic limit threshold values of damage states for different damage measures are assumed by engineering judgment [6] as given in table 4.

Table 4 : Damage states [6]

Damage measures	Damage States(DS)			
	Non structural (DS-1)	Slight (DS-2)	Moderate (DS-3)	Extensive (DS-4)
Maximum Inter-storey drift ratio (MISD)	0.05%	0.10%	0.20%	0.70%
Maximum base shear (MBS)	5%W	10%W	15%W	20%W
Maximum roof drift ratio (MRD)	0.10%	0.50%	1%	2%
Maximum isolator displacement (MID)	$0.2D_{max}$	$0.4D_{max}$	$0.8D_{max}$	$1.2D_{max}$
Maximum Roof floor acceleration (MRFA)	0.1g	0.2g	0.3g	0.4g

Where, W = total seismic weight of the structure; D_{max} = maximum design displacement of the isolator. The choice of intensity measure (IM) is important in relation to describe the earthquake severity and to scale the earthquake records in the incremental dynamic analysis (IDA). There are various IMs which are used by researchers namely, peak ground acceleration(PGA), peak ground velocity, spectral acceleration of first mode period, Sa (T1), peak ground displacement (PGD), arias intensity, etc. Among different IMs, Peak Ground Acceleration is extensively used as the IM due to its efficiency, practicality, and hazard computability [6] by many researchers for analysing the base isolated structures. With this intention, PGA is considered as IM in present study.

5. Results and Discussions:

The results extracted from the non-linear time history analysis for the low and medium rise building subject to the selected earthquake data is represented the plots in figure 10 to 18 by further scaling to different values of PGA for maximum base shear(MBS), maximum isolator displacement(MID), maximum roof drift ratio(MRD), maximum interstory drift ratio(MISD) and maximum roof floor acceleration(MRFA).

Mean IDA(Incremental Dynamic Analysis) curves are drawn for the base shear, maximum isolator displacement, maximum roof drift ratio, maximum inter storey drift and maximum roof floor acceleration. The mean IDA curves represent the average seismic response to the increasing levels of Peak ground acceleration. Mean IDA curves characterize the behavior of Structure and the effectiveness for performance evaluation under the defined damage states. Figure 19 to 23 shows the plot of mean IDA curves MBS, MISD, MRD,MID and MRFA, for the low and medium rise buildings respectively. The observations are as below;

1. In low rise building, the base shear exceeds damage state 1 for medium PGA, whereas the isolated models do not exceed damage state 1 even at high PGA. In low rise building models, the base shear values exceed Damage state 3 at higher PGA, while the isolated base models stay within damage state 1, even at high PGA, in reducing base shear reflecting effectiveness of base isolation. Similar trend observed in medium rise buildings w.r.t base shear, wherein damage state 2 is reached at higher PGA for Fixed base models, these Fixed base models cross damage state 1 at high PGA, isolated models stay within DS-1 at all levels of PGA considered (refer to figure19).
2. Both low rise and medium rise buildings are within the damage state-1 (refer figure 20) in terms of displacement experienced by the Isolators even at higher PGA levels. In low rise building, a constant difference is seen at all PGA levels
3. Maximum roof drift ratio, for fixed base models exceeds damage state-1, which indicated slight damage. In low rise buildings, significant reduction in roof drifts is observed at high PGA levels, which is also evident at low PGA. In case of medium rise buildings, reduction in interstorey drifts is not evident up to medium PGA, thereafter slight reduction in roof drift at high PGA is observed(refer figure 21).
4. For maximum interstorey drift ratio, fixed base models have highest maximum interstorey drift ratio, all fixed base models exceed damage state-3 indicating extensive damage. In low rise models the base isolation is successful in controlling the damage caused by interstorey drift at all levels of PGA, as seen in figure 22 . In medium rise building, no reduction in interstorey drift is observed up to medium PGA, thereafter slight reduction in observed, and stays within damage state-3 for LRB isolated base models.
5. Very high damage is caused by maximum top floor acceleration as evident from figure 23 low rise building reach the damage state 4 indicating potential collapse, whereas the base isolated low rise buildings stay within damage state-1, which is more than 75% reduction in top floor acceleration, in low rise buildings. Similar trend is also observed for medium rise buildings.

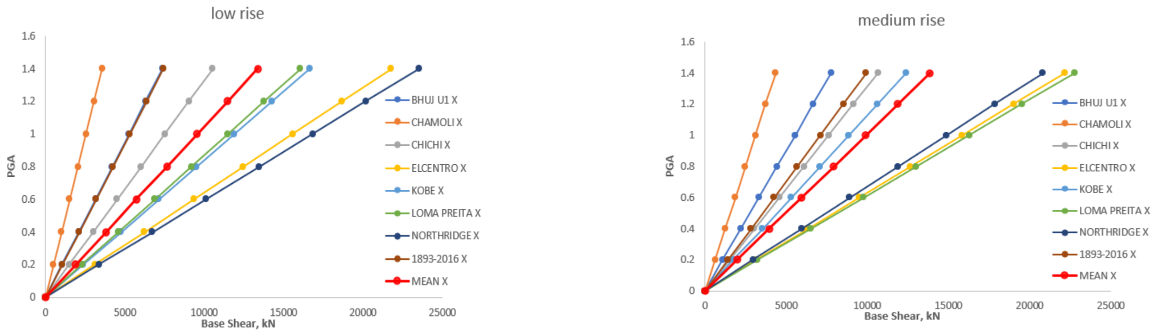

Fig 10 . IDA curves of Base shear generated for fixed base models of low and medium rise building

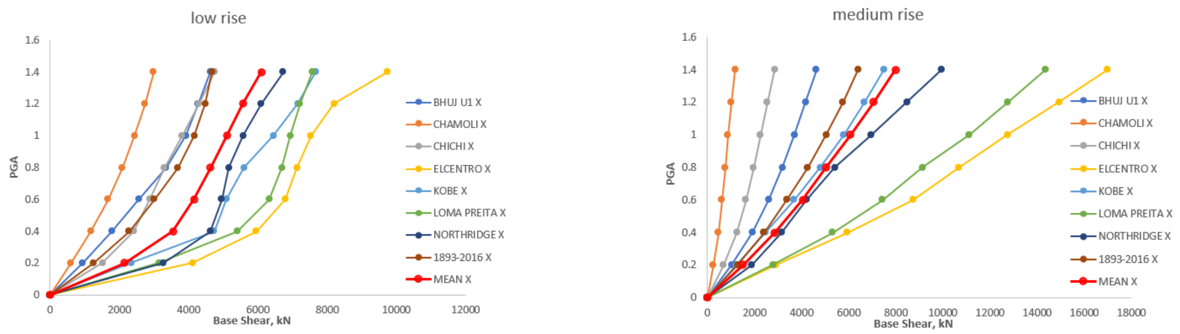

Fig 11. IDA curves of Base shear generated for base isolated models of low and medium rise building

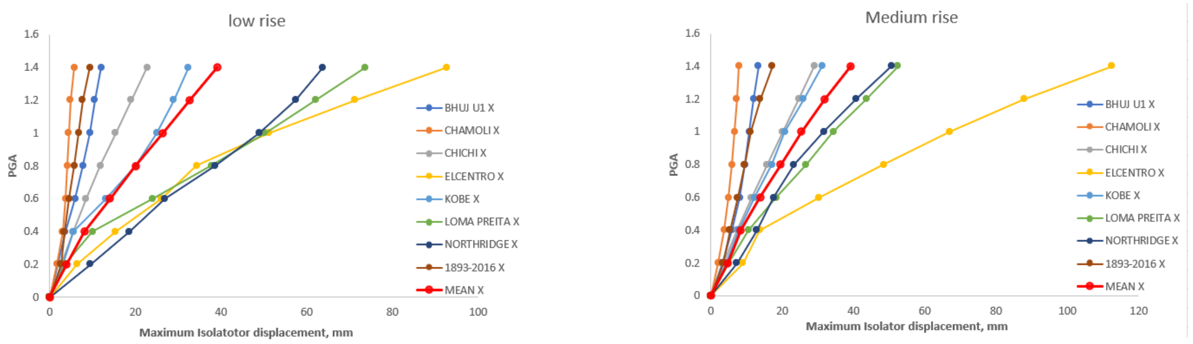

Fig 12 . IDA curves of maximum isolator displacement generated for base isolated models of low and medium rise building

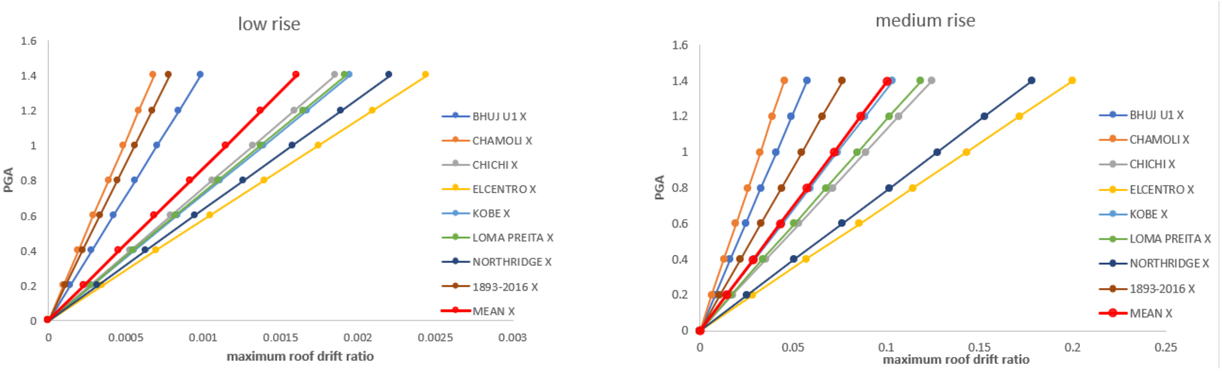

Fig 13. IDA curves of maximum roof drift ratio generated for fixed base models of low and medium rise building

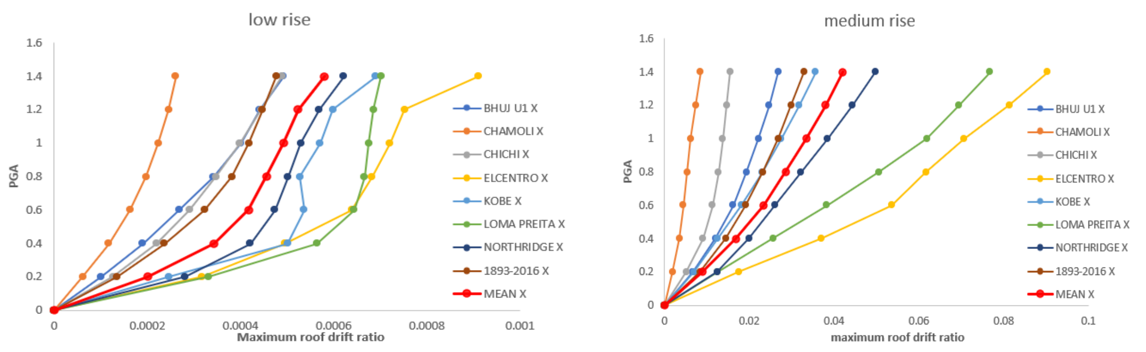

Fig 14 . IDA curves of maximum roof drift ratio generated for base isolated models of low and medium rise buildings

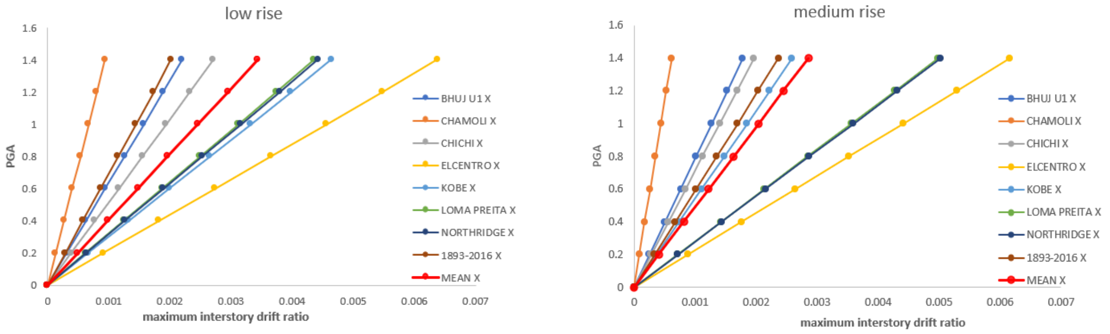

Fig 15. IDA curves of Maximum inter storey drift ratio generated for fixed base models of low and medium rise building

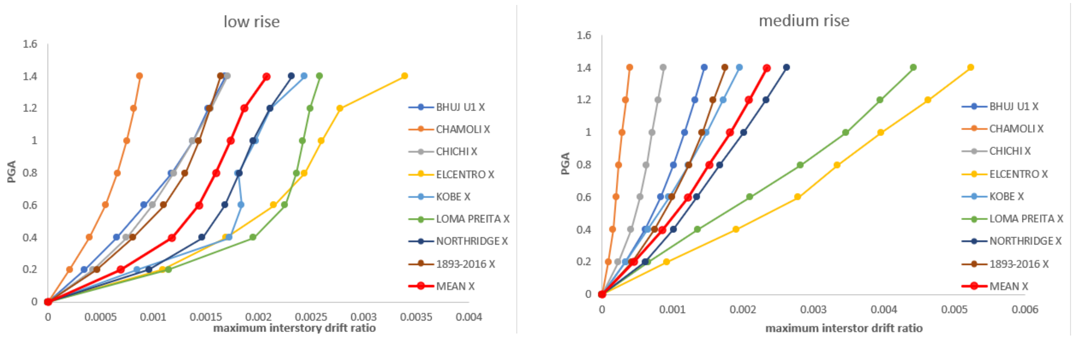

Fig 16. IDA curves of maximum interstorey drift ratio generated for base isolated models of low and medium rise building

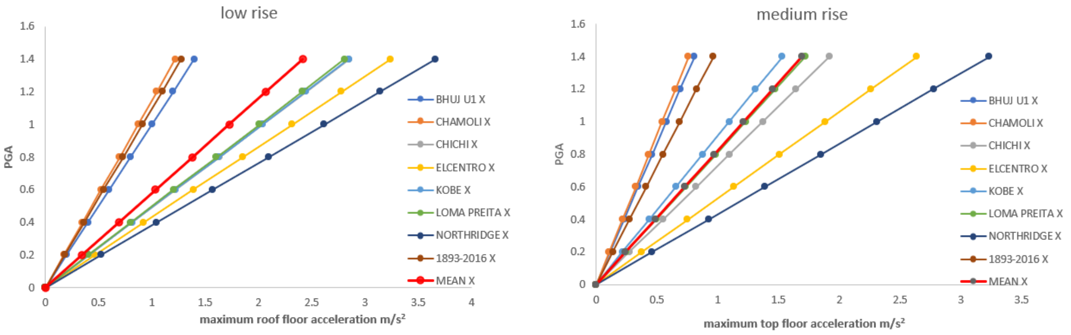

Fig 17. IDA curves of maximum roof floor acceleration generated for fixed base models of low and medium rise building

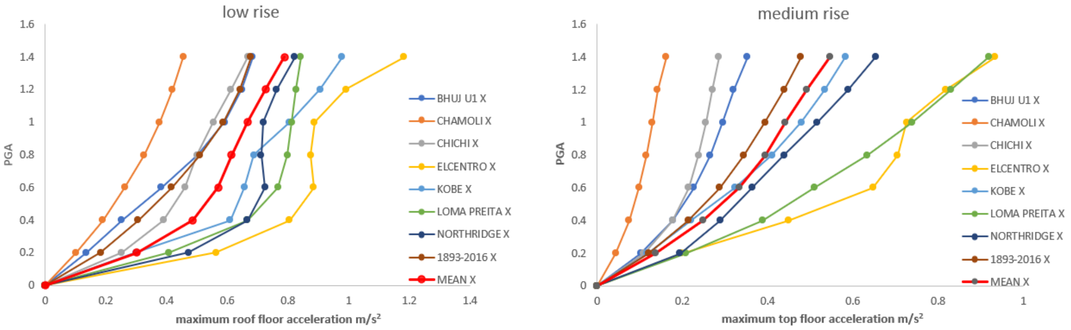

Fig 18. IDA curves of maximum roof floor acceleration generated for base isolated models of low and medium rise building

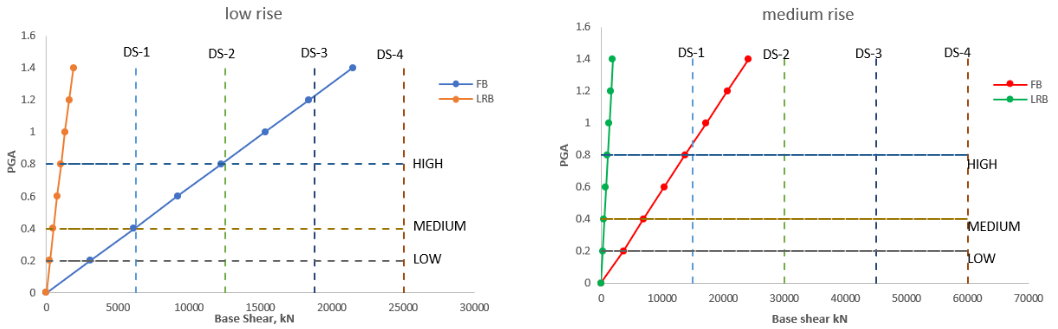

Fig 19. Mean IDA curves for Base Shear of low and medium rise building

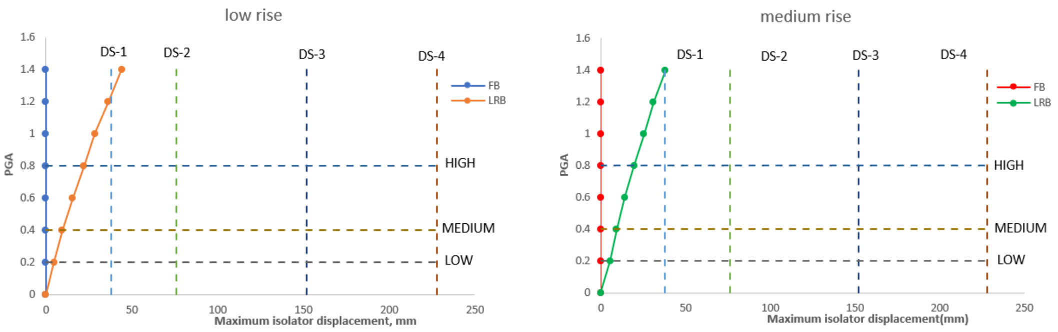

Fig 20. Mean IDA curves for maximum isolator displacement of low and medium rise building

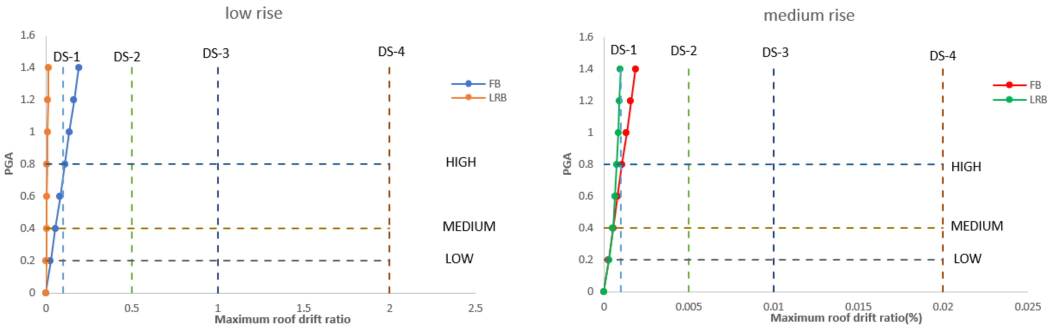

Fig 21. Mean IDA curves for maximum roof drift ratio of low and medium rise building

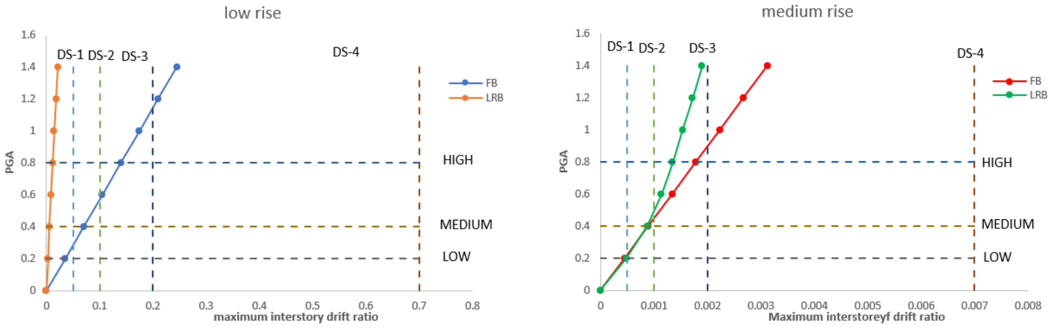

Fig 22. Mean IDA curves for Maximum inter story drift ratio of low and medium rise building

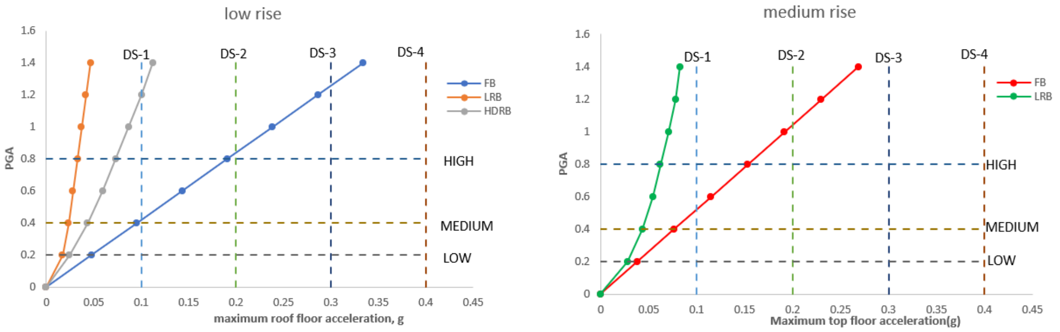

Fig 23. Mean IDA curves for maximum roof floor acceleration of low and medium rise building

6. Conclusions

1. Base shear due to time history load cases are highest for fixed base models of both low and medium rise buildings. Substantial reduction in base shear is observed for low and medium rise buildings with base isolation, indicating considerable reduction if effects due to seismic forces.
2. Roof drifts are observed to be highest in Fixed base models of low and medium rise buildings when compared with base isolation.
3. Interstorey drift ratio is highest in fixed base buildings of low and medium rise for all time history cases and is reduced for isolated base models, this reduction is more for low rise buildings, compared to medium rise buildings.
4. Story acceleration is highest in low and medium rise buildings with fixed base and is reduced with base isolation.
5. From mean IDA curves it is seen that Base isolation is effective even at high PGA levels for the considered low and medium rise buildings.
6. The results of Incremental Dynamic Analyses of structures suggest that the method can become a valuable additional tool of seismic engineering. IDA addresses both demand and capacity of structures. The Mean IDA curves offer a comprehensive view of the seismic response of the structure, accounting for the uncertainty and vulnerability in the response. IDA curves are valuable tools for Structural engineers, researchers and decision makers to asses and mitigate seismic risk.

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